Search for Large Extra Dimensions at the Tevatron [a]

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We report a search for large extra spatial dimensions in $p\bar{p}$ collisions at a center of mass energy of 1.8 TeV at the Tevatron. We present recent DØ results on graviton-mediated exchange processes, using events containing a pair of electrons or photons. No evidence for signal is found, allowing to place the most restrictive lower limits on the effective Planck scale at the order of 1 TeV for several number of extra dimensions.

1 Introduction

The complete unification of particle interactions might require the presence of additional spatial dimensions, three of which are within the reach of our senses, the others being compactified at distances of the order of 10^{-32} m. In a recent model, inspired by string theory, Arkani-Hamed, Dimopoulos and Dvali (ADD),[1] suggested that there may be only one single scale in particle phenomena, the electroweak scale, which also corresponds to an effective Planck scale $M_S \approx 1$ TeV, provided that there exist extra dimensions compactified at far larger radii than the Planck length, as large as 1 mm. In this model, particles of the Standard Model (SM) are localized in our four-dimensional world, but gravitons are allowed to propagate in all the large extra dimensions.

Signatures for large extra dimensions depend on whether the gravitons (G) in particle interactions are real (emitted in collisions) or whether they are virtual. Thus, the impact of virtual gravitons can be observed in reactions such as $q\bar{q} \to G \to \gamma\gamma$, or $gg \to G \to e^+e^-$. Graviton emission can lead to an apparent violation of energy and momentum (as well as of angular momentum) conservation when the graviton has energy momentum components transverse to the brane of the SM, e.g., $q\bar{q} \to G + g$, or $e^+e^- \to G + \gamma$. The characteristic signatures for contributions from virtual graviton correspond to abnormally high formation of massive systems, while direct emission of graviton results in an increase of events with large apparent imbalance in transverse momentum (or "missing E_T", $\not\!\!E_T$), in particular events with only one jet in the final state (mono-jet).

Limits on M_S of ≈ 1 TeV have already been reported from LEP,[2] and somewhat weaker limits (from searches for virtual graviton contributions) have been published by experiments at HERA.[3] In this paper we report a search for large extra dimensions at the Fermilab Tevatron using approximately 127 pb^{-1} of $p\bar{p}$ data collected at $\sqrt{s} = 1.8$ TeV by DØ from 1992-96.

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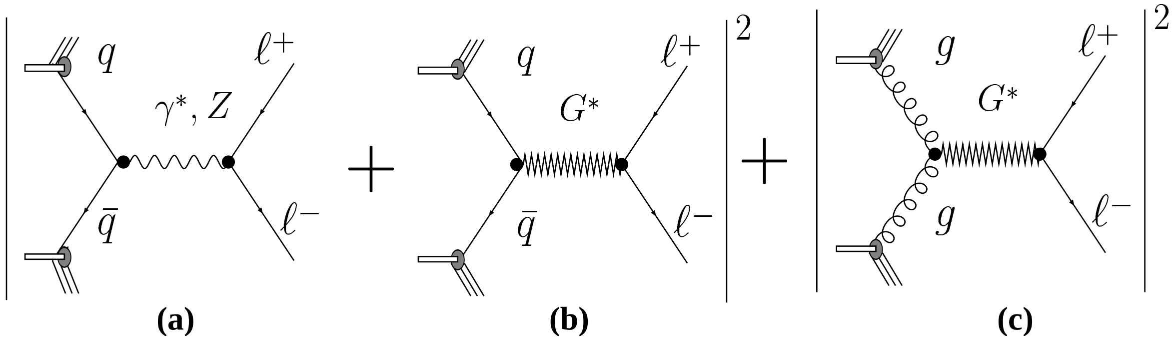

Figure 1: Feynman diagrams for dilepton production in the presence of large extra dimensions. G represents graviton exchange. (a) correspond to the SM amplitude contribution, (c) is the pure graviton contribution and (b) the interference between the two.

2 Virtual Graviton Effects

In this paper, we focus on DØ results on virtual graviton effects.[4] The amplitude for graviton exchange has to be added coherently to that of the SM, because processes such as $q\bar{q} \to Z/\gamma^* \to e^+e^-$ and $q\bar{q} \to G \to e^+e^-$ can provide important interference terms. Figure 1 represents the Feynman diagrams for dilepton production in the presence of large extra dimensions.

Three phenomenological formulations of the problem have appeared in the literature.[5,6,7] They are equivalent, and differ only in their definitions of M_S. DØ follows the more sophisticated phenomenology of Ref.[5], which contains a dependence of the cross section on the number of extra dimensions n. The correspondence between the three definitions of scale is that $M_S(n = 5) \approx M_S(\lambda = +1)$ of Ref.[7] and $M_S(n = 4) = \Lambda_T$ of Ref.[6].

3 Analysis at DØ

DØ bases its analysis on both di-electron and di-photon signals. Since DØ did not have a central magnetic field in Run I, the analysis ignores the particle charges, and the cross section is therefore examined as a function of the dielectron (M_{ee}) or diphoton ($M_{\gamma\gamma}$) invariant mass, and $|\cos\theta^*|$, where θ^* is the angle of the e or γ relative to the line of flight of the ee or $\gamma\gamma$ system in the helicity frame. The analysis follows the Cheung-Landsberg extension[8] of previous studies that were based on the use of only the mass variable in the problem.

Because the instrumental background (e.g., a jet mimicking a photon or an electron) in this search is small at large E_T,[9] the signals for ee and $\gamma\gamma$ are added together in the comparison of data to theory. This maximizes the reach of the experiment to highest mass scales because it allows a loosening of the usual strict electromagnetic (EM) shower requirements on both photons and electrons. The analysis ignores charged particle tracking information in the detector, and relies purely on the observation of di-EM systems of high invariant mass ($M_{EM,EM}$). The theory used to describe the contributions from the SM and virtual gravitons is a leading order (LO) calculation. Nevertheless, the expected yields are corrected for higher order effects through an application of a common "K-factor" of 1.3 (which probably underestimates the expected yield from gravitons at largest $M_{EM,EM}$, thus resulting in conservative limits on their existence). The criteria for the final 1250 candidate events require only two acceptable EM showers, each with $E_T > 45$ GeV, and no missing transverse momentum ($\not{E}_T < 25$ GeV). There are no requirements placed on jets.

The data are compared to a LO parton generator,[8] augmented with a parameterized DØ detector simulation package that models the acceptance, resolution, vertex smearing, impact of having additional vertices from overlapping multiple interactions, and introduces a transverse impact to the di-EM system (assuming that it is the same as in the inclusive Z data of DØ[10]). As indicated above, the calculation applies a uniform K-factor correction to all SM and virtual graviton cross sections. The CTEQ4LO parton distribution functions (PDF) are used to integrate the matrix elements over the incident parton distributions (with checks performed using other PDFs). Most of the di-EM events arise from prompt di-photon, and, to a lesser extent, from e^+e^- production (usual SM processes). The background from other channels, such as $W+$ jets, $W+\gamma$, WW, $t\bar{t}$ are negligible. The largest instrumental background ($\approx 7\%$ of the di-EM signal) is from multijet production, where two jets are misidentified as EM showers.

4 Results

Figure 2a displays a comparison of data with the Monte Carlo model containing contributions only from the SM for the invariant mass of the di-EM system, and shows a good agreement with expectations.[8]

With no excess apparent beyond expectations of the SM, DØ proceeds to calculate a lower limit on the graviton contribution to the di-EM cross section. The cross section as a function of $M_{EM,EM}$ and $|\cos\theta^*|$ can be written as:

$$\sigma = \sigma(SM) + \eta \times \sigma_4 + \eta^2 \times \sigma_8 \tag{1}$$

where $\eta = F/M_S^4$, with $F = 2/(n-2)$ for $n > 2$,[5] and where $\sigma(SM)$ represents the SM cross section, σ_8 the pure graviton contribution, and the term linear in η is the interference between the two. The addition of graviton exchange increases the yield at large $M_{EM,EM}$, especially for small values of $|\cos\theta^*|$.

The expected sensitivity to $|\eta|$ is obtained from a fit of the above formula for the cross section (σ) to Monte Carlo samples that do not contain graviton components, and have statistics appropriate to the DØ data, which corresponds to an integrated luminosity of 127 events/pb. Such fits yield an expected sensitivity of $\eta < 0.44$ TeV^{-4}. The DØ fits are performed using a Bayesian formalism that yields the likelihood for $|\eta|$, and the expected limit of 0.44 TeV^{-4} corresponds to an upper limit at 95% confidence.

The result of a similar fit to the data yields an upper limit of 0.46 TeV^{-4}, which provides a lower limit on the value of M_S that depends somewhat on the value of n. In particular, $M_S > 1.44$ TeV for $n = 3$, and $M_S > 0.97$ TeV for $n = 7$. The results of a similar analysis in the dielectron channel from the CDF collaboration have recently become available,[11] and are somewhat less restrictive than the DØ ones. The combined Tevatron limits are expected to yield further improvement over the actual excluded range of M_S.

5 Summary

In summary, DØ has presented first results of a search for contributions of virtual gravitons to production processes at the Tevatron. In the context of the ADD scenario of large extra dimensions with a single mass scale in the domain of particle interactions, the DØ analysis of massive electrons and photons pairs constrains the mass scale M_S to be greater than 1.0$-$1.4 TeV. These limits at the 95% confidence level are comparable to the final results anticipated from LEP. More studies are forthcoming from CDF and DØ on real graviton emission (mono-jet events), as well as on virtual graviton exchange. By the end of the Tevatron Run II, the sensitivity to M_S will reach 3 to 4 TeV. Beyond that, the LHC will be able to probe effective Planck scales up to 10 TeV.

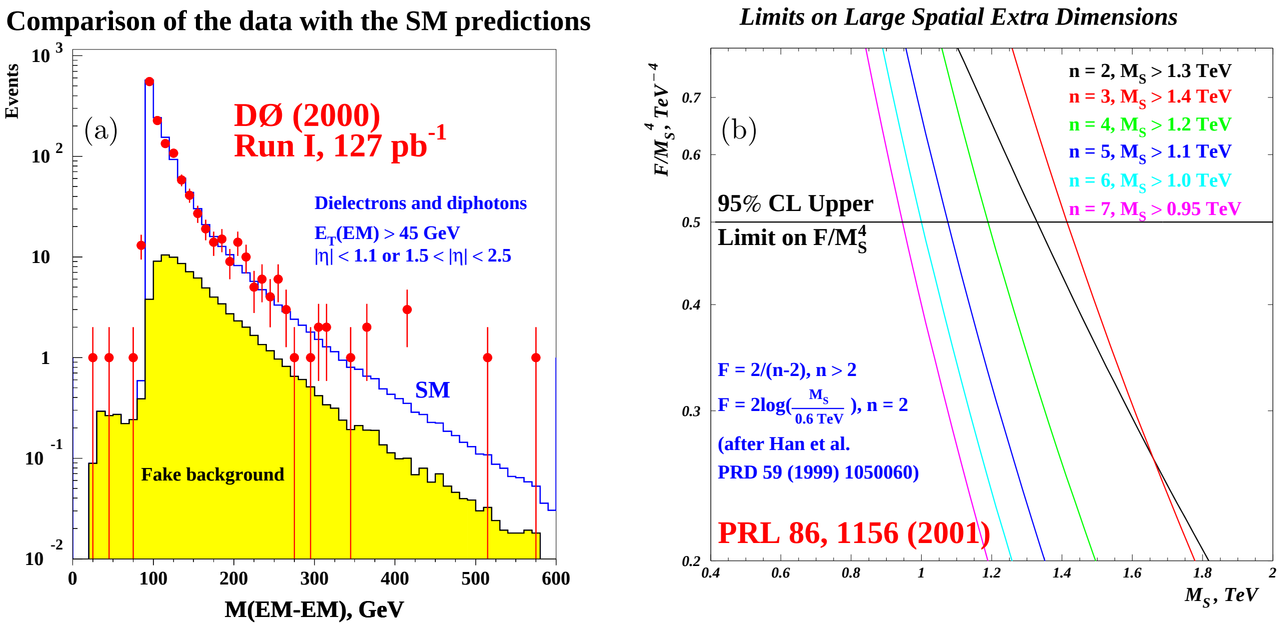

Figure 2: (a) Comparison of the invariant mass of the di-EM system with the Monte Carlo that contains contributions only from the SM; (b) Limits on the effective Planck mass scale M_S as a function of the number of extra dimensions.

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